

Giant eruptions of very massive stars¹

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ABSTRACT

Giant eruptions or supernova-impostor events are far more mysterious than true supernovae. An extreme example can release as much radiative energy as a SN, ejecting several M_{\odot} of material. These events involve continuous radiation-driven outflows rather than blast waves. They constitute one of the main unsolved problems in stellar astrophysics, but have received surprisingly little theoretical effort. Here I note some aspects that are not yet familiar to most astronomers.

1. Introduction

Let me steal a metaphor from Tom Wolfe. Some of us think that a Demon lives near the Eddington Limit. If you (as a massive star) try to approach that limit, he intervenes before you get very close to it. He shakes you so violently that you lose mass and energy, and throws you back away from the edge. After watching this happen to a number of stars, we have never seen the Demon's face. In hindsight his behavior almost makes sense in terms of physics, and it dramatically alters the evolution of very massive stars. But the only certain factor is that no theorist predicted it.

This idea grew from several disparate topics. Three decades ago, Luminous Blue Variable stars (LBVs) attracted attention because their sporadic mass-loss events could explain why there are no yellow and red supergiants above $L \sim 10^{5.9} L_{\odot}$ [1]. LBVs are closer to $(L/M)_{\text{Edd}}$ than other stars in the same part of the H-R diagram. Meanwhile the parameters of η Carinae's huge outburst in 1830–1860 became clear; as usual one really good example provided better clues than dozens of less extreme ones. That event expelled 10 to 30 M_{\odot} of material and the same amount of light as a typical supernova, in a timescale roughly 100 times as long as a SN event, and the star survived. By 1990 the role of episodic mass loss in the most massive stars was widely recognized [2]. But then an odd thing happened: After

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1995, astronomers almost seemed to forget this topic! When mass loss in ordinary hot-star winds was reassessed downward around 2005, invalidating the published evolutionary tracks [3], experts began to propose eruptive loss instead. In fact its role had been familiar to many people 15 years earlier.

Meanwhile, SN surveys revealed abnormal explosions in other galaxies. Instead of obvious blast waves, they produced slower, more continuous outflows resembling η Car’s great eruption [4]. Some were labeled “Type IIn supernovae,” which implies pre-existing circumstellar ejecta. And occasionally the star survived! We call such cases Supernova Impostors, with η Car as the obvious prototype. Equally embarrassing, a few SN events had precursor outbursts, which seemed paradoxical in any textbook view. One supernova observed in 2012 already had the name SN 2009ip!

Few researchers believe that any one instability mechanism produced all the eruptions that I’ve mentioned. Several types probably co-exist: (1) Core-collapse SNaes that had unusual extended envelopes when they exploded; (2) other core phenomena, mostly but not entirely related to nuclear processes; (3) the Demon mentioned earlier, a hypothetical radiative/fluid instability (or instabilities) that can arise when $L/M > 0.5(L/M)_{\text{Edd}}$; (4) binary interactions, mass transfer, and/or mergers; and (5) whatever we haven’t thought of. Incidentally, number 4 is frequently offered as a panacea, but the statistics make that very unlikely. Since all these conjectural types of eruption share the same radiative outflow physics, *they look alike* when viewed from outside.

As you might guess, the situation has become too confused for a newcomer to learn easily. Some basic fallacies have propagated in the literature. For example, most supernova specialists assume that progenitors of type IIn must be LBVs, based on faulty logic. Many recent authors have applied the term LBV to stars that *might* belong to that class but are unproven, and to other stars that *don’t* belong. The big evolutionary differences between luminous and less-luminous LBVs are seldom acknowledged. Various explain-all “models” consist mainly of words, cartoon sketches, and/or computer runs with many unadvertised assumptions. Reciting their defects would fill many pages. Thus, I earnestly advise everyone to be wary of groupthink – and equally wary of claims that some paper has revolutionized the topic.

Since this is an account of some concepts, and not of the literature, few papers will be cited here. For general background see articles by many authors in [5], and older references in [2] – a review which, amazingly, has not been superseded nor seriously disproven after 20 years (except that it said too little about rotation). Each citation below implies “and other references noted therein.”

2. Radiative physics in a giant eruption

Let’s begin with a clear definition. A stellar “giant eruption” is a *super-Eddington mass outflow*, driven by continuum radiation pressure. It is not driven by a shock wave, though shocks may propagate through the flow. It’s opaque, so the photosphere is located at a fairly large radius in the outflow. The eruption usually persists for months or years, much longer than any relevant dynamical timescale. It is quite likely to be non-spherical, e.g. the famously bipolar case of η Car. The word “eruption” is especially apt in some models that behave like geysers, with instability propagating inward while expelling mass outward [2]. Ordinary large LBV outbursts are not giant eruptions, but they have physical similarities.

We often mention the Eddington factor $\Gamma = L/L_{\text{Edd}}$, where $L_{\text{Edd}} \approx 4\pi cGM/\kappa$. Most of the opacity κ is due to Thomson scattering, but the relatively small absorption opacity determines the size of the photosphere (see below). Eta Car’s great eruption had $\Gamma \sim 2$ to 10, but SN 2011ht and SN 2009ip had $\Gamma > 50$. Occasionally it is claimed that such large values cast doubt on the entire concept. In fact, however, the basic outflow math for $\Gamma \rightarrow \infty$ is not much different from $\Gamma \sim 4$. The star’s mass M then has little effect and everything depends on L and on the sonic point where the flow originates; since higher eruption luminosities generally have larger size scales, the outflow speeds remain below 1000 km s^{−1} in most cases even with $\Gamma > 50$.

In principle a giant eruption can originate in more than one way. The Demon instability mentioned above, for example, might be an “opacity-modified Eddington limit” affair not far below the star’s photosphere, or (more likely) it may involve strange-mode instabilities in the notorious high-opacity layers where $T \sim 3 \times 10^5$ K [2]. Either way, a lot of extra radiation pushes material while diffusing outward. A core-collapse SN can also become a giant eruption. Initially, of course, a SN blast wave occurs. In a normal case it eventually reaches the star’s surface, with familiar results. But suppose the star is surrounded by a large opaque envelope 100 times as dense as an ordinary stellar wind – something resembling the wind that η Car had a century ago. It’s easy to show that photons then diffuse outward ahead of the blast wave. (See, e.g., [9]. Supernova enthusiasts perversely call this phenomenon “shock breakout,” but it’s really photon breakout.) The diffusing radiation accelerates a giant eruption that precedes the blast wave. The shock doesn’t reach the outflow’s photosphere until a time well after the maximum brightness.

Logically, this account of a giant-eruption SN transfers the problem to *why* that dense circumstellar stuff was there. It requires a big precursor outflow, a less luminous giant eruption in the last few years before the main explosion. But this seems counter-intuitive, because the tiny pre-SN core with its rapid nuclear timescale is not supposed to know about the star’s outer layers, and vice-versa. This looks like evidence that the Demon lives in the

core of the star, rather than the outer layers as some of us have usually supposed. But if that’s true, then why is there an LBV instability strip in the HR diagram, representing only the outer layers? And why does it explain the HRD’s upper limit so nicely? (See [2]). Are there two different Demons? Or more? These are among the biggest questions in stellar astrophysics, because no one has a credible answer yet.

Unfortunately a super-Eddington flow is difficult to calculate, because 3-dimensional effects may be crucial. The ejected mass and velocities in η Car’s giant eruption do not match simple 1-D outflow calculations [6,7]. This shouldn’t surprise us, since it’s conceptually “a light fluid driving a heavy one” à la Rayleigh-Taylor. R-T instabilities within a star imply convection, but a giant eruption is a supersonic outflow. Likely result: local mass concentrations form and photons escape preferentially along the easiest paths between blobs – thus reducing the effective κ so far as radiative acceleration is concerned. Indeed the ejecta around η Car show obvious granulation with reasonable size scales. This phenomenon in a super-Eddington flow has been called “porosity” [7], though “granulation” may be a better term depending on the topology of the mass condensations. In order to avoid having to do a fresh 3-D model for every observed eruption, *we need a general, albeit rough, empirical prescription* based on many numerical simulations – in the same spirit as mixing length theory for convection. (Some authors have recently asserted that 1-D models work better than I said above, see [8] and useful refs. therein; but if this is true, it needs to be confirmed by 3-D investigations.)

Next let me say something about observed continuum slopes and emission lines. Giant eruptions, LBV eruptions, and other mass outflows typically have apparent temperatures between 7000 and 9000 K at maximum brightness [2]. This fact is a consequence of opacity physics, and does not imply that the outbursts had similar causes. The average temperature of escaping radiation represents the “thermalization depth” where $\sqrt{(3\tau_{\text{tot}}\tau_{\text{abs}})} \sim 1$. A crucial fact is that opacity decreases rapidly below $T \sim 7500$ K, and *very* rapidly below 6500 K. Thus we find some interesting generalities for a wind or outflow with a given luminosity [10]. First, a moderate mass-loss rate can produce apparent temperatures around 8000 K, defined in a particular way. But reducing that to 7000 K requires a substantially larger density or mass-flow rate; 6000 K implies a rather huge rate; and much lower temperatures are unlikely in practical terms. (This is analogous to the Hayashi limit.) Since temperatures in this range also have bolometric corrections near zero, it is entirely natural that opaque outflows of all kinds often look like $T \sim 7500$ K at maximum brightness.

(*Caveat:* These temperatures are defined in a particular way [10], and other definitions give different values. The temperature at $\tau \approx 2/3$ is *not* a good choice, since it has no physical significance in a convex diffuse configuration.)

And here’s a nice consequence for emission lines. The thermalization depth mentioned above usually occurs at Thomson scattering depths $\tau_{sc} \sim 2$ or 3, a consequence of the opacity dependences. Emission lines are formed in the diffuse outflow outside that radius, i.e. in regions where $\tau_{sc} \sim 1$ to 2. This is the range where Thomson-scattered line wings are apparent, recognizable, and moderate – just like the spectra of the best-observed giant eruptions (e.g. [11,12]). *When we see moderate Thomson-scattering wings on the Balmer emission lines, with a visual continuum slope like $T \sim 7000$ to 12000 K, then we’re probably looking at a super-Eddington flow.*

At this point I feel bound to warn against a particular spectroscopic fallacy that has caused confusion. *Absorption-line spectra of opaque winds cannot be classified with stellar spectral types.* Compare, for instance, a star with $T_{eff} = 6500$ K vs. an opaque wind with the same photosphere temperature. The star’s atmosphere has practically no material below 5200 K, but outer parts of the wind can be substantially cooler than that. Therefore it is possible for the wind to show “cool” absorption features along with those that we expect to see in a 6500 K spectrum. This pitfall led to a serious misinterpretation of the light-echo spectrum of η Car’s great eruption. Contrary to some well-publicized claims [13], in fact that spectrum seems reasonably consistent with the super-Eddington flow type of model [14]. It would be helpful, though, to have some genuine theoretical spectrum models for this case – a difficult undertaking.

We now have a sizable fund of excellent data on LBVs and related stars, η Car and other supernova impostors, and on giant-eruption supernovae; observers have done their job well. But theorists have given this topic far less attention than it deserves. As I implied earlier, *this subject is relatively unexplored territory* for theory.

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Finally here’s a second gratuitous literary allusion. So far as I know, ref. [15] contains the earliest account of a “continuing explosion” qualitatively reminiscent of a stellar eruption. It employed Carolinum, and η Car used to be in a constellation named Robur Carolinum; so maybe that author knew something that we don’t. On the other hand, he favored a nuclear process that is difficult to scale up to the size of a giant eruption.

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